Utilization of Birefringent Fiber as Sensor of Temperature Field Disturbance

Filip DVOŘÁK, Jan MASCHKE, Čestmír VLČEK

Faculty of Military Technologies, University of Defence, Kounicova str. 65, 662 10 Brno, Czech Republic

filip.dvorak@unob.cz, jan.maschke@email.cz, cestmir.vlcek@unob.cz

Abstract. *The paper deals with utilization of induced birefringence sensitivity to temperature field in birefringent optical fibers. The propagating optical wave and optical fibers are described by means of coherency and Jones matrices, which are decomposed into unitary matrix and spin matrices. The development of polarization caused by temperature field is interpreted on the Poincaré sphere by means of MATLAB® environment. The temperature sensitivity of Panda and bow-tie fiber has been measured for circular polarization excitation. Curves of intensity fluctuation caused by the temperature dependence are presented.*

Keywords

Induced birefringence, temperature dependence, birefringence sensitivity, beat length, Jones matrix, coherency matrix, spin matrices, Poincaré sphere, temperature sensor.

1. Introduction

Polarization preserving fibers utilize an induced birefringence, which creates expressive difference in velocity of two polarization modes and so that it limits coupling between them by the defects along the fiber. During the excitation of one polarization mode this fiber maintains the polarization of optical wave. Utilization is in a number of applications in the area of information transition or in the area of sensor, e.g. interferometric sensor as fiber gyroscopes, etc. Significant group of polarization preserving fibers are fibers, where optical birefringence is created by means of delimitate cladding parts with different temperature coefficient than proper cladding. This construction creates different mechanical stress of the fiber core and thereby it induces the optical birefringence. Typical representatives of this group are the fibers denoted as bow-tie and PANDA. These fibers can be characterized by the two linear polarization modes, which propagate with the different velocity. The phase shift which thus arises, changes polarization state on the fiber output. The principle of birefringence creation leads to its important temperature dependence and after that to the temperature dependence of output phase shift. Based on the measured values of phase shift 0.735 and 0.757 rad.m^{-1}°C^{-1} on the 1m of fiber bow-tie and PANDA with beat length 1 and 2 mm respectively [1] we can suppose orientation value of phase shift about 0.75 rad.m^{-1}°C^{-1}. High sensitivity on the ambient temperature was also investigated during measurement of effect of torsion on the transient properties and so that has been measured more detailed [2].

Along the propagation of only one polarization mode, temperature dependence is not substantial in many applications. The birefringence sensitivity on the temperature and possibility of temperature effect on the long parts of fiber, which multiple fiber sensitivity on the temperature, should lead to the idea to utilize these properties for measurement of temperature during excitation of both polarization modes. This application should require relative complicated signal processing from the optical and electronic point of view. But it is possible to create very sensitive temperature sensor which reacts on the variations of temperature field. Its utilization can be, e.g. for guarding of territories towards the entry of persons or to come close to the equipment. The possibility of fiber distribution enables the monitoring of large territory.

2. Theoretical Analysis

A birefringent fiber is in its substance the linear optical retarder, more precise multiple optical retarder. Important characteristic quantity is the beat length z_z defined as the length, where the phase shift between the polarization modes arises equal to the 2π. According to the fact that birefringence value determines the temperature extensibility, we define the beat length for 20°C as reference z_{20}. In the next considerations we will suppose only effect of temperature on the different velocity of propagation, but not the temperature extensibility, which has no substantial effect on the variation of phase shift on the beat length.

The polarization development of the wave propagating along the fiber and fluctuation of output polarization with temperature can be described by means of Stokes parameters and interpreted on the Poincaré sphere. For description we will use less commonly usual way of transition to the Stokes parameters by means of coherency matrix for description of optical wave and Jones matrix for description of fiber.

For optical radiation we can use coherency matrix **J** as follows

$$\mathbf{J} = \begin{bmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{bmatrix} = \begin{bmatrix} \langle E_x E_x^* \rangle & \langle E_x E_y^* \rangle \\ \langle E_y E_x^* \rangle & \langle E_y E_y^* \rangle \end{bmatrix} \tag{1}$$

where E_x, E_y are components of electric field intensity in the axes x, y,

E_x^*, E_y^* are components complex conjugate to the E_x, E_y,

$\langle \ \rangle$ is symbol for mean value,

J_{xx}, J_{xy}, J_{yx}, J_{yy} are components of coherency matrix.

Coherency matrix can be decomposed by means of unitary matrix and spin matrices. This decomposition can be made also on the body of quaternions, which are in unique relation with the spin matrices [3].

$$\mathbf{J} = \frac{J_{xx} + J_{yy}}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{J_{xx} - J_{yy}}{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} + \\ + \frac{J_{xy} + J_{yx}}{2}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + \frac{i\left(J_{xy} - J_{yx}\right)}{2}\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \tag{2}$$

Coefficients in the individual matrices respond to the Stokes parameters S_0, S_1, S_2, and S_3. Relation (2) can be written as

$$\mathbf{J} = \frac{1}{2}\left[S_0\mathbf{I} + S_1\boldsymbol{\sigma}_1 + S_2\boldsymbol{\sigma}_2 + S_3\boldsymbol{\sigma}_3\right] \tag{3}$$

where **I** is $\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ - unitary matrix

and $\boldsymbol{\sigma}_1 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, $\boldsymbol{\sigma}_2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$, $\boldsymbol{\sigma}_3 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$ are the spin matrices.

Indices of spin matrices are matched to the indices of Stokes parameters. Towards usual notation the indices are cyclic shifted about value one. This fact must be given in the consideration at solution of relations between the spin matrices.

Coherency matrix can be written as

$$\mathbf{J} = \frac{1}{2}\begin{bmatrix} S_0 + S_1 & S_2 - iS_3 \\ S_2 + iS_3 & S_0 - S_1 \end{bmatrix} = \\ \frac{S_0}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{1}{2}\begin{bmatrix} S_1 & S_2 - iS_3 \\ S_2 + iS_3 & -S_1 \end{bmatrix} = \frac{S_0}{2}\mathbf{I} + \frac{1}{2}\mathbf{H} \tag{4}$$

From the mathematic point of view [4] we can interpret the matrix (3) as follows. If there exists the set of orthogonal unitary vectors $\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3$, so that to the vector

$$\mathbf{S}_u = S_1\mathbf{u}_1 + S_2\mathbf{u}_2 + S_3\mathbf{u}_3 \tag{5}$$

the Hermitean matrix can be assign, in our case the matrix **H** in the relation (4). This relation is called isomorphism.

If optical wave described by the matrix **J** propagates through the optical environment described by the Jones matrix **L**, so for coherency matrix of output optical wave **J**′ the following relation is valid

$$\mathbf{J}' = \mathbf{LJL}^{+} \tag{6}$$

where $\mathbf{L}^+$ is hermitean conjugate matrix to the matrix **L.**

After substitution (4) to the (6) we obtain according to $\mathbf{LIL}^+ = \mathbf{I}$ the result

$$\mathbf{J}' = \frac{1}{2}\left[S_0\mathbf{I} + \mathbf{LHL}^{+}\right]. \tag{7}$$

Whether optical system does not contain any partial polarizers but consists entirely of rotators and retardation plates, a general Jones matrix **L** is only unitary [5]. The relation $\mathbf{LHL}^+$ represents, regarding to the unitarity of matrix **L**, rotation of vector S_u representing by the matrix **H**, about angle and around the axis defining Euler parameters [4]. This conception enables general solution, which is not necessary for our application.

Maximal sensitivity on the temperature variation can be reached by the same excitation of both polarization axes i.e. excitation by the circular polarization, or linear polarization with 45° orientation with respect to the polarization axes. Excitation by the circular polarization is more suitable because we don't need to know position of polarization axes. We consider the fiber as linear retarder with phase shift $\delta = n2\pi + \varphi$, where n is the number of integer multiples of beat length and φ is the part which is already not integer multiple of beat length.

Coherency matrix of circular polarized optical wave is given by the relation

$$\mathbf{J}_c = \frac{S_0}{2}\begin{bmatrix} 1 & \mp i \\ \pm i & 1 \end{bmatrix} \tag{8}$$

where S_0 is the total intensity.

The sign discriminates clockwise and counter clockwise polarization. The clockwise polarization is described by $J_{xy}(-i)$ and $J_{yx}(+i)$. The clockwise and counter clockwise orientation are discriminated by an observer who is situated in the path of the beam (specifically, far out on the Z-axis) and is looking toward the light source, which is at the origin of coordinates [6].

For simplicity we will consider the fiber in the position, where polarization axes are identical with coordinate system of measurement. Jones matrix can be expressed as follows

$$\mathbf{L}_\delta = \begin{bmatrix} e^{-i\delta/2} & 0 \\ 0 & e^{i\delta/2} \end{bmatrix}. \tag{9}$$

The coherency matrix of output optical wave $\mathbf{J}'$ can be obtained by the substitution of (8) and (9) to (7).

$$\mathbf{J}' = \mathbf{L}_\delta \mathbf{J}_c \mathbf{L}_\delta^+ = \frac{S_0}{2}\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - i\begin{bmatrix} 0 & \pm e^{-i\delta} \\ \mp e^{i\delta} & 0 \end{bmatrix}\right). \qquad (10)$$

After the decomposition of the second matrix in (10) on the spin matrices, we get the relation corresponding to the vector in orthogonal coordinate system $\mathbf{u_1}, \mathbf{u}_2, \mathbf{u}_3$:

$$i\begin{bmatrix} 0 & e^{-i\delta} \\ e^{i\delta} & 0 \end{bmatrix} = \frac{S_0}{2}\left(\cos\delta\, \boldsymbol{\sigma}_3 + \sin\delta\, \boldsymbol{\sigma_2}\right) \equiv \qquad (11)$$
$$\equiv \frac{S_0}{2}\left(\cos\delta\, \mathbf{u}_3 + \sin\delta\, \mathbf{u_2}\right)$$

The values cosδ and sinδ correspond to the Stokes parameters S_3 and S_2. According to the fact that parameter S_1 equals to zero, the point describing the polarization state in the output moves for variation of δ along to the circle, created by the cut of the Poincaré sphere perpendicular to the axis u_1, coming through the pole, corresponding to the circular polarization.

The birefringent fiber is considered as multiple linear retarder. On the beat length z_{20} which is reached at 20°C it comes for this temperature to the phase shift 2π between the polarization modes. For the fiber length $l = nz_{20} + \Delta l$, where n is integer multiple of beat length and Δl is part of fiber which is not integer multiple of beat length, it comes to the phase shift $\varphi_{20} = n2\pi + \varphi(\Delta l)$. Interpretation of polarization development for excitation by the circular polarization on the Poincaré sphere corresponds to the n orbits along the circle coming from the pole, defined by cut of Poincaré sphere by the plane limited by the axes of Stokes parameters S_2, S_3, to the partial shift corresponding to $\varphi(\Delta l)$.

For temperature variation phase shift changes to the value $\varphi(\square) = \varphi_{20} \pm \Sigma_i \Delta\varphi_i \pm \Delta\varphi(\Delta l)$, where the sum is only over i - beat lengths, for which the temperature field effects.

According to the fact that phase shift on the part of fiber Δl and for temperature variation is negligible with the relation to the variation $\pm \Sigma_i \Delta\varphi_i$ on the i-elements, we can suppose temperature variation $\Phi(\vartheta) = \varphi(\vartheta) - \varphi_{20}$ directly as $\pm\Sigma\Delta\varphi_i$ and it is valid

$$\Phi(\vartheta) = \sum_i \Delta\varphi_i \,. \qquad (12)$$

This simplification comes from the fact, that for beat length e.g. 2 mm variation of temperature field can affect up to 500 beat lengths and measured values of phase shift on 1m and 1°C in the similar fibers are 0.735 and 0.757 rad.m^{-1}.°C^{-1} [1].

Development of polarization by the effect temperature field variation can be observed on the Poincaré sphere in Fig.1. With respect to the values of phase shift, the variations of temperature field will show variations of phase and corresponding shift of point along the Poincaré sphere surface, at the effect of temperature variation on the longer part of fiber there will be a multiple phase shift of 2π and multiple circulation of point along the circle on the Poincaré sphere described above. Because only detection of changes is of interest, the polarization development can be described by means of observing output polarization under some angle with respect to the polarization axes. The setting of output polarizer with angle 45° with respect to the polarization axes is useful. In this case, intensity of output optical wave changes from maximum at phase shift 0° to the minimum at the phase shift π. The values correspond to the points on the axis S_2.

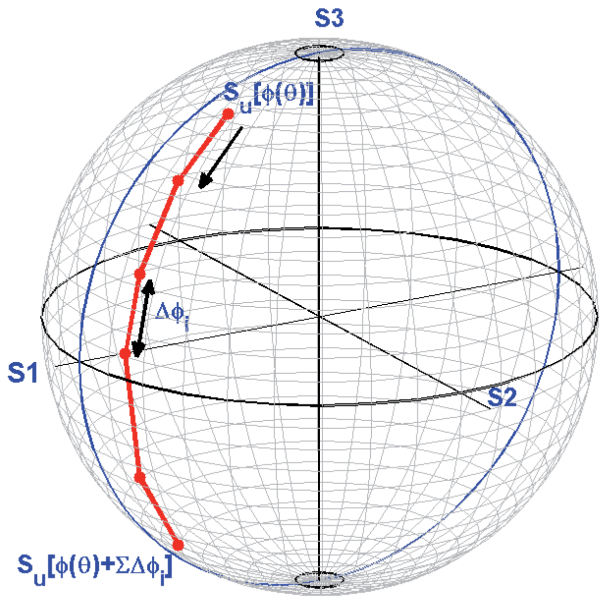

Fig. 1. Development of polarization with excitation by circular polarization and with changes of temperature field.

3. Experimental Results

The arrangement of a work place for experiments is given in Fig. 2. Polarization preserving fiber PANDA for wavelength 633 nm is wound on the paper spool with diameter 14.5 cm. The length of the fiber is 8 m, 7 m is directly on the spool and 1 m is free. The winding of the coil is as follows: 3/6 of turns are on the upper side and temperature variation will be effect immediately on them, 3/6 windings are on the bottom side of the coil and it is isolated from temperature effect by the paper spool. Linear polarized radiation of He-Ne laser is launched through retarder λ/4 into the fiber input, so the fiber is excited by the radiation with circular polarization. The output radiation from the fiber is led on the polarizer-analyzer oriented over 45° with respect to the polarization axes. The maximal output power from the fiber was 100 μW. The output intensity is measured by means of a power meter with multimeter controlled by the PC with program AMEX, which enables direct cooperation with Excel and processing of results. Using program part enables time measurement of output values, in our case with interval approximately 1 s (true value of interval is 0.975 s).

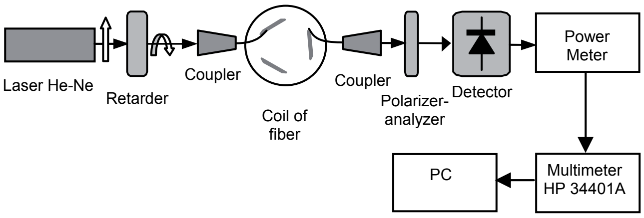

Fig. 2. Arrangement of work place.

Measurement was realized at typical room temperature. With respect to the temperature fluctuations, evidently by the influence of persons presence, warm rising in measurement equipment etc., the state of polarization and also the intensity on the output of polarizer changes in the time interval from ones to tens minutes.

The btained results of output intensity measurement at the different measurement times and only effects of typical room temperature fluctuations are presented in Fig. 3.

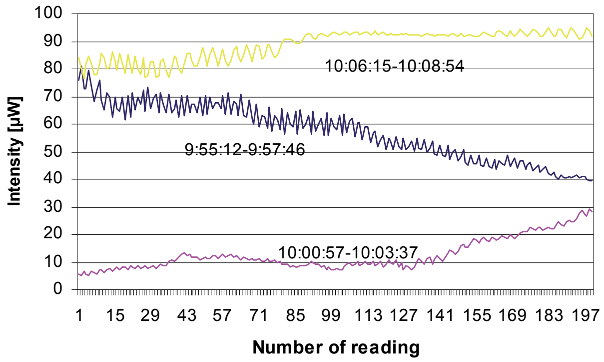

Fig. 3. The intensity fluctuation caused by typical room thermal field disturbance at 3 different times.

Disturbance of temperature field was simulated by different methods. A typical example is i.e. illumination of the fiber by the light of a bulb from a different distance, insertion of some thermal body to a different distance etc. In Fig. 4, 5, 6 and 7, we can see the time dependence of intensity for disturbances of thermal field caused by a ceramic plate and a hand, expressed by the order of reading.

In Fig. 4 the ceramic plate heated on 37°C is used for thermal field disturbance, which can simulate, i.e. temperature of a human hand. With regard to the size of the plate (16x12 cm^2) it covers the diameter of the coil on one side from the 80%, so that from the whole length of the coil in the upper side of the coil (3/6), this is approximately 3,5 m, the plate effects approx. on the length of the fiber equal to 2.9 m.

In Fig. 4 in the time of 50th reading (approx. in 50th sec) a ceramic plate heated on 37°C inserted at distance 6 cm, simulated the human hand. From the graph it is clear that in the time of insertion output polarization is very strongly changed and step by step gets near to the steady state at the higher temperature, where polarization will again slowly fluctuate. The whole time of measurement in this case was 200 s. In Fig. 5 there is the same experiment but the plate is removed in the time of 100th reading and the polarization is going back to the beginning state.

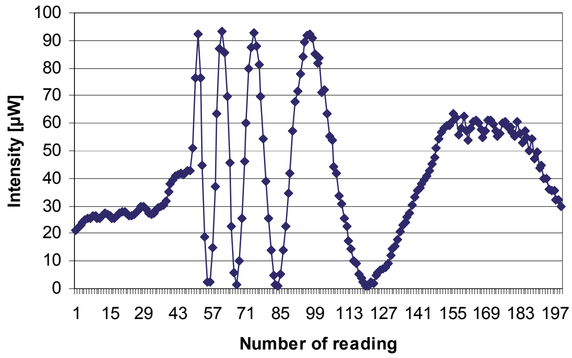

Fig. 4. The intensity fluctuation caused by ceramic plate thermal field disturbance from the time of 50th reading to the end of reading.

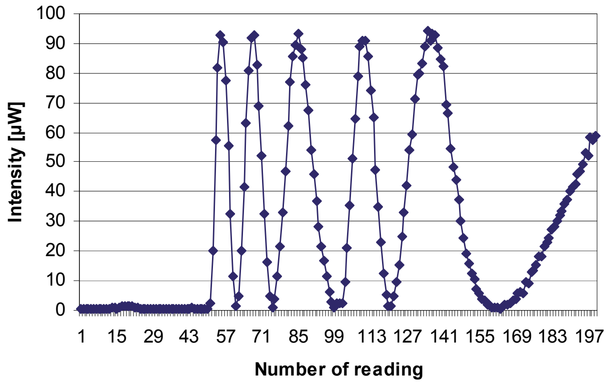

Fig. 5. The intensity fluctuation caused by the ceramic plate thermal field disturbance from the time of 50th reading to the time of 100th reading.

As an interesting demonstration, the examples of disturbance of thermal field by the placing of a hand at the identical arrangement as in the cases of the ceramic plate in Fig. 4 and 5 are given in Fig. 6 and 7. It is evident that the diagrams with the plate (37°C) and human hand are similar.

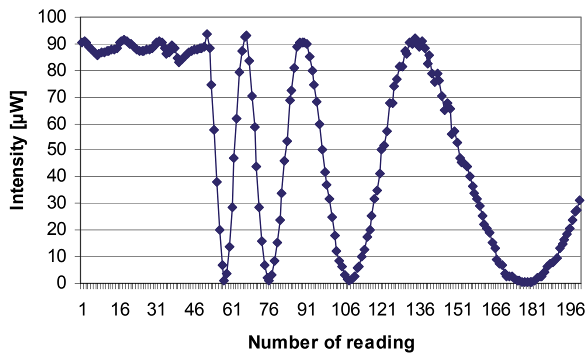

Fig. 6. The intensity fluctuation caused by hand thermal field disturbance from the time of 50th reading to the end of reading.

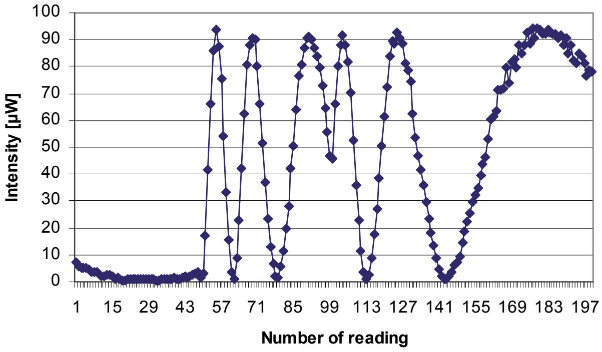

Fig. 7. The intensity fluctuation caused by hand thermal field disturbance from the time of 50th reading to the time of 100th reading.

It is necessary to accent, that measured results prove that the reaction time of the observed fiber is in order of 10^0s. Together with the high sensitivity it enables not only application in temperature sensor systems detecting disturbance of thermal field, but after a deeper analysis also at regulation systems, which need fast reaction on the temperature disturbance.

The given results are valid in the presented configuration, where the effect is limited on the part from the whole length of the fiber. It is evident, that during the incidence of thermal variation on the longer parts of the fiber, sensitivity increases with the length of the fiber and with practically the same preserving of the reaction time.

4. Conclusions

The presented results are only the demonstrations, which show possibilities of applications of polarization preserving fibers with excitation of both polarization axes as highly sensitive elements and their possible use in temperature sensor systems, where they can react on the thermal field, or in regulation systems, with fast reaction on the temperature changes. These applications evidently need stable configuration of sensors, or eventually the work of a system at a different wavelength, enabling creation of a compact set of an optical source, a fiber, a detector and polarization elements.

Acknowledgements

This work has been supported by the grant GACR 102/09/0550: Optical beams study for atmospheric static and mobile communications, and research plan FVT 0000403: Development, integration, administration and security of communication and information systems (C4I2) in NATO environment, of the Ministry of Defense, Czech Republic.

References

[1] ZHANG, Z., LIT, J. W. Y. Temperature sensitivity measurement birefringent polarization-maintaining fibres. *SPIE* vol. 1580 *Fiber Optic Components and Reliability*, 1991.

[2] DVOŘÁK, F., MASCHKE, J., VLČEK, Č. Study of time fluctuation of polarization of polarization preserving fibers. In *Proceedings of 19th IMEKO World Congress*. Lisbon (Portugal), 2009, p. 80 - 83.

[3] CUBIÁN, D. P., ARCE-DIEGO, J. L., FREY, R. Application of the Quaternions theory to the analysis of the semimagnetic semiconductor microcavity. *SPIE vol.5036 Photonics, Devices, and Systems II.* Prague (Czech Republic), 2002, p. 511 - 517.

[4] KORN, G. A., KORN, T. M. *Mathematical Handbook for Scientists and Engineers*. McGraw-Hill, 1968.

[5] JONES, R. C. A new calculus for the treatment of optical systems. I. Description and discussion of the calculus. *J. Opt. Soc. Am.*, 1941, 31, p. 488 - 493.

[6] SHURCLIFF, W. A. *Polarized Light, Production and Use.* Cambridge, Massachusetts: Harvard University Press, 1962.

[7] TALPA, M. Automated measurement with table calculator Microsoft Excel. In *Proceedings of the Conference STO-7.* Brno (Czech Republic), 1999, p. 235 - 238 (in Czech).

About Authors

Filip DVOŘÁK was born in 1977. He received the MSc. degree in 2004 from the Brno Military Academy, branch Special Communication Systems. He is now a student of the doctoral program with the focus on the modeling of fibers and optical components by the matrix methods with the application of MATLAB.

Jan MASCHKE was born in 1942. He received the MSc. degree in 1965 and PhD. degree in 1978. He was the teacher at the Technical School at Liptovský Mikuláš and at Military Academy since 1968, and associate professor of the Department of Electrical Engineering since 1985. He was retired in 2005. His research work was focused on the problems of fiber optics and fiber sensors.

Čestmír VLČEK was born in 1946. He received the MSc. degree in 1969 and PhD. degree in 1980. He was the teacher at the Military Academy since 1969, associate professor since 1985 and head of Electrical Engineering and Electronics Department since 1997 and professor since 2000. His research work during the last years was aimed to the problems of optoelectronic signals and systems, single mode fiber components modeling, atmospheric optical communication systems and analysis of sensors for military applications.